MOTOR BRUSH TESTING FOR MARS AND VACUUM

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ABSTRACT

Brush motors have been qualified and flown successfully on Mars missions, but upcoming missions require longer life and higher power. A test program was therefore undertaken to identify the best brush material for operation in Mars atmosphere. Six different brush materials were used in 18 identical motors and operated under various load conditions for a period of four weeks in low-pressure CO2. All motors performed acceptably, with accumulated motor revolutions between 98 and 144 million revolutions, depending on load. A proprietary silver-graphite material from Superior Carbon (SG54-27) appears to be the best choice for long life, but even the stock copper-graphite brushes performed reliably with acceptable wear.

The motors from the CO2 test were then cleaned and run in vacuum for 2 weeks. The difference in results was dramatic, with 5 motors failing catastrophically and wear rates increasing by orders of magnitude for the SG54-27 material. Three brush materials survived the test with no failures: SG54-27 with a proprietary Ball Aerospace impregnation, a silver-graphite-molybdenum disulfide material from Superior Carbon (SG59), and a copper sulfide-graphite material also from Superior Carbon (BG91).

INTRODUCTION

Background

Traditionally, brushless DC or stepper motors have been used in space applications where the highest reliability is required. Sliding electrical contacts have gained a reputation for unreliable operation in vacuum, especially at the high speeds encountered in brush motors. Two factors have led to adopting brush motors for Mars applications. First, there is an atmosphere; although very thin, it can have a highly beneficial effect on brush operation and rotor heat dissipation. Second, and probably more directly responsible, is the emphasis of the low-budget, short schedule missions. There is often not sufficient time or budget to develop appropriate brushless motors; mass constraints also favor brush motors.

The Sojourner Rover was the first Mars mission to make extensive use of brush motors[1]. Performance requirements were modest; average power input was less than .25 watt for each motor, and the entire flight mission covered about 100 meters, or less than 3 hours of continuous operation. The same motors were initially selected for the Robotic Arm on the Mars Polar Lander, but the requirements for longer life and higher

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power could not be met. A new motor was designed and fabricated by the American Technology Consortium (ATC). The motor incorporated silver-graphite brushes, and it provided a great improvement in life[2]. The attempt to use the same motor in a vacuum application, however, was not satisfactory.

The 2003 Mars Mission

The Athena program, scheduled to launch in 2003, plans to use 30 brush-type motors of various sizes. The rover drive motors are required to push the 75 kg vehicle to a top speed of 6 cm/s and do so for at least 10 km. The motor for the sample drill must be capable of handling 20 watts continuously for at least 100 million revolutions. Because of the extensive reliance on brush motors and the requirements for high power and long life, it was deemed necessary to obtain more accurate data on brush material behavior in the Mars atmosphere.

TEST PROGRAM

Overview

The test program was limited in order to obtain useful results for a minimum cost, utilizing residual motors and existing test fixtures. Only easily obtainable, commercial materials were selected for the brushes. Some custom formulations of more exotic materials have shown good results[3] but were not considered for this test.

The focus of the test was to investigate brush performance vs. current density in a CO2 environment to simulate the atmosphere of Mars. Three motors were prepared with each brush material. One motor was utilized as a drive (high current) coupled to a second motor acting as a brake (slightly lower current), and a third motor was run with no load (very low current).

For a practical Mars mission, it is highly desirable to operate the flight motors in an ambient Earth environment for various subsystem and system tests. An initial 24 hour no-load run was included in the test program to check this capability. Vacuum operation is not a requirement for the 2003 Mars mission; this was included for the potential benefit of other space programs.

Motor Brush Materials

Due to the very low pressure of the Mars atmosphere, the selection of motor brush materials was based on high altitude and vacuum applications. Following is a list of the selected materials, and brief justification. A scanning electron microscope was used to identify constituent elements and approximate concentrations measured by surface area.

SG54-27 – a silver-graphite from Superior Carbon. This material has been qualified in CO2 on the Robotic Arm motors with very good results. Approximately 10% silver, with proprietary compounds added for high-altitude operation.

SG54-27-V – the above material with a proprietary wet lubrication impregnation ("Vac-Kote") by Ball Aerospace. Several sources reported using this modified material successfully in vacuum.

SG59 – a silver-gaphite-MoS_2 from Superior Carbon, commonly used for slip rings in vacuum. Very low contact resistance and low electrical noise[4]. Approximately 55% silver and 18% MoS_2.

BG91 – a copper-sulfide graphite material, also from Superior Carbon. A previous test of 11 materials identified this as a superior performer in vacuum[5]. Approximately 17% copper sulfide. Might also be known as D91

BG91-V – Vac-Kote applied to the BG91 material.

Copper-Graphite – the stock brush material supplied with the Maxon RE025 motors. Included as a baseline, with minimal expectations. Approximately 30% copper content.

Motor

The motors used in the test were commercial units with neodymium iron magnets and graphite brushes.

Manufacturer, part #:	Maxon #118757
Rated Voltage:	48 V
Test Voltage:	30 V
Terminal Resistance:	33.7 Ω
Torque Constant:	.0897 Nm/A
Speed Constant:	11 rad/s/V (106 rpm/V)
Commutator Diameter:	.005 m (0.20 in)
No. of Segments:	11
Mass:	.13 kg

Set-up

Motor brushes were prepared from the various materials by NC machining to match the arc shape of the original brushes. Shunt wires were potted into the brushes using conductive silver epoxy. The original brush springs were retained, which produced a pressure of 96 kPa at the commutator. All motors were clamped to an aluminum plate. For the loaded tests, drive and brake motor shafts were connected together by flex couplings (see Figure 1). A heat exchanger with fluid loop was attached to the back of the aluminum plate to cool the assembly. The plate was mounted in an environmental chamber, with external 37.3 ohm resistors providing load for the brake motors. Drive motor current and brake motor current were recorded continuously.

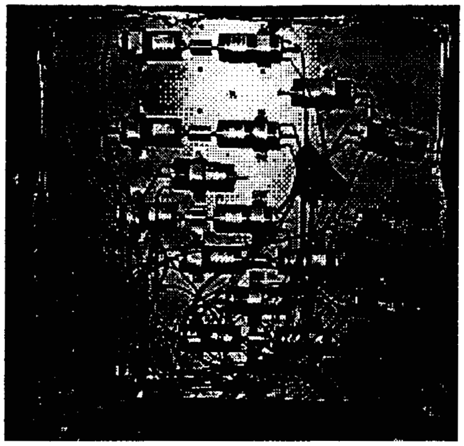

Figure 1. Motors Mounted to Test Plate

Procedure
The testing sequence and conditions are summarized below. All tests were conducted at 30 volts input.

Test	Duration	Load	Atmosphere	Post-test operations
#1	24 hours	No-load	Earth	Inspect, Clean of brush debris
#2	72 hours	No-load	8 kPa CO_2	Inspect
#3	2 weeks	Full load	8 kPa CO_2	Inspect
#4	2 weeks	Full load	8 kPa CO_2	Inspect, Clean of brush debris
#5	2 weeks	Full load	Vacuum	Inspect

RESULTS

Motor revolutions, current densities, and wear rates are presented in tables 1, 2, and 3. Wear rate is defined as the linear brush wear (at the centerline of the arc-shaped brush) divided by the distance traveled at the commutator surface. Electrical performance is provided in tables 4 and 5. Anomalies and inspection observations are given in the following notes.

Test #1 Notes: Both of the wet-lubricated materials produced cohesive debris which accumulated in the commutator slots. SG54-27-V was the worst offender, with debris build-up also noted on the leading edge of the brushes.

Test #2 Notes: Significant debris accumulations in the commutator slots for SG54-27V, SG59, and Stock materials. Debris build-up on brush edges for SG54-27-V.

Test #3 Notes: SG54-27 motors almost completely free of debris. Very heavy build-up in commutator slots of SG54-27-V, Stock, and BG91-V drive motors.

Test #4 Notes: All motors were briefly checked for no-load current draw before beginning the loaded test. SG54-27-V and BG91-V drive motors initially took in excess of 3 watts no-load, SG54-27-V drag motor initial draw was just under 2 watts. These high currents fell back to lower levels after a few seconds of operation. SG54-27-V and BG91-V drive/brake motors were markedly less efficient in the first hour or so of loaded operation. For this period, SG54-27-V drew an input power of 12.3 watts and registered an overall efficiency of 16% for the drive and brake combination. At the end of the test, the SG54-27 and SG59 motors had the least debris in the commutator slots. The debris from the "Vac-Kote" impregnated brushes had to be mechanically cleaned from the slots; all other brush material debris was removed by low pressure air.

Test #5 Notes: 5 motors failed, all with excessive current draw. BG91-V drive motor brushes were broken after coming into contact with bubbled-up epoxy on the overheated rotor. The Stock drive motor was stopped soon after high-current operation was observed; terminal resistance of 18 ohms returned to normal (32 ohms) after cleaning debris out of the commutator slots. All other failed motors endured more extensive heating periods, and ultimately suffered breakdown of the winding insulation. The SG59 drive and no-load motors had considerable commutator wear, .07 mm and .05 mm, respectively. The BG91 no-load motor drew extremely low power after 4 days of vacuum operation: less than 0.06 watts. A close-up of the brush / commutator area of the BG91 drive motor is shown in Figure 2.

<u>Addendum: Results of Continued Testing</u>

Two preliminary qualification tests have been conducted for specific applications on the Athena Rover, with excellent results.

One Maxon RE025 part # 118752 was prepared with SG54-27 brushes and tested in 8 kPa CO_2 for 47 million motor revolutions at a brush current density of 25.5 A/cm^2, with a resulting brush wear rate of 1.3×10^{-11}. Power input was then increased to over 30 watts (current density 33.6 A/cm^2); resultant wear rate was 8×10^{-11} after 60 million additional motor revolutions with no failure.

Three Micro Mo 1727-18 motors were tested at 16 volts in 8 kPa CO_2 for a scan actuator application. The test was a no-load start-stop with dynamic braking and direction reversal. Each motor survived 1.9 million start-stop cycles, with 218 million motor revolutions accumulated. There were no failures or anomalies. Motor brushes were stock copper-graphite, and average wear rate was 4×10^{-11}.

Table 1. Motor Revolutions, Current Density, and Wear Rates for Tests #1 and #2

			Test #1: 24 h, Earth ambient			Test #2: 72 h, .8 kPa CO2		
Motor #	Material	Load Condition	Motor Revs (x10^6)	Current Density (A/cm^2)	Wear Rate cm/cm x10^-10	Motor Revs (x10^6)	Current Density (A/cm^2)	Wear Rate cm/cm x10^-10
1	SG54-27	No-Load	4.5	0.3	2.6	13.2	0.3	0.0
2	SG54-27	No-Load	4.5	0.3	5.2	13.2	0.3	0.0
3	SG54-27	No-Load	4.5	0.3	2.6	13.2	0.3	0.0
4	SG54-27-V	No-Load	4.5	0.6	2.6	13.2	0.6	0.0
5	SG54-27-V	No-Load	4.5	0.6	1.3	13.2	0.6	0.9
6	SG54-27-V	No-Load	4.5	0.6	1.3	13.2	0.6	0.4
7	BG91	No-Load	4.5	0.2	2.6	13.2	0.3	1.3
8	BG91	No-Load	4.5	0.2	0.0	13.2	0.3	0.4
9	BG91	No-Load	4.5	0.2	5.2	13.2	0.3	0.4
10	BG91-V	No-Load	4.5	0.3	3.9	13.2	0.3	0.4
11	BG91-V	No-Load	4.5	0.3	7.9	13.2	0.3	0.0
12	BG91-V	No-Load	4.5	0.3	7.9	13.2	0.3	0.9
13	SG59	No-Load	4.5	0.6	3.9	13.2	0.6	1.3
14	SG59	No-Load	4.5	0.6	6.4	13.2	0.6	0.4
15	SG59	No-Load	4.5	0.6	3.9	13.2	0.6	1.8
16	Stock	No-Load	4.5	0.4	9.3	13.2	0.4	0.4
17	Stock	No-Load	4.5	0.4	7.9	13.2	0.4	0.9
18	Stock	No-Load	4.5	0.4	7.9	13.2	0.4	0.0

Table 2. Motor Revolutions, Current Density, and Wear Rates for Tests #3 and #4

			Test #3: 2 weeks, .8kPa CO2			Test #4: 2 weeks, .8kPa CO2		
Motor #	Material	Load Condition	Motor Revs (x10^6)	Current Density (A/cm^2)	Wear Rate cm/cm x10^-10	Motor Revs (x10^6)	Current Density (A/cm^2)	Wear Rate cm/cm x10^-10
1	SG54-27	Drive	39.5	6.7	0.0	40.5	6.6	0.1
2	SG54-27	Brake	39.5	6.3	0.0	40.5	6.2	0.0
3	SG54-27	No-Load	62.3	0.4	0.1	63.8	0.4	0.0
4	SG54-27-V	Drive	39.5	7.7	0.0	40.5	7.7	0.1
5	SG54-27-V	Brake	39.5	6,3	0.0	40.5	6.2	0.0
6	SG54-27-V	No-Load	62.3	0.6	0.0	63.8	0.7	0.0
7	BG91	Drive	39.5	7.1	0.0	40.5	6.7	0.3
8	BG91	Brake	39.5	6.1	0.0	40.5	6.0	0.1
9	BG91	No-Load	62.3	0.1	0.0	63.8	0.1	0.0
10	BG91-V	Drive	39.5	6.7	0.0	40.5	6.8	0.6
11	BG91-V	Brake	39.5	6.1	0.0	40.5	6.1	0.1
12	BG91-V	No-Load	62.3	0.2	0.0	63.8	0.2	0.0
13	SG59	Drive	39.5	7.0	2.2	40.5	7.6	1.8
14	SG59	Brake	39.5	6.9	0.3	40.5	6.9	0.3
15	SG59	No-Load	62.3	0.3	0.4	63.8	0.4	0.7
16	Stock	Drive	39.5	7.6	5.2	40.5	7.5	4.7
17	Stock	Brake	39.5	6.6	1.0	40.5	6.5	1.3
18	Stock	No-Load	62.3	0.4	1.9	63.8	0.4	1.8

Table 3. Motor Revolutions, Current Density, and Wear Rates for Test #5

			Test #5: 2 weeks, vacuum			
Motor #	Material	Load Condition	Motor Revs (x10^6)	Current Density (A/cm^2)	Wear Rate cm/cm x10^-10	Notes
1	SG54-27	Drive	26.4	6.9	35.6	Failure (220 h)
2	SG54-27	Brake	26.4	5.5	0.2	
3	SG54-27	No-Load	33.7	0.4	41.1	Failure (178 h)
4	SG54-27-V	Drive	35.8	6.5	0.2	
5	SG54-27-V	Brake	35.8	5.6	0.2	
6	SG54-27-V	No-Load	56.4	0.4	0.0	
7	BG91	Drive	35.8	5.9	0.6	
8	BG91	Brake	35.8	5.2	0.2	
9	BG91	No-Load	56.4	0.1	0.0	
10	BG91-V	Drive	4.6	5.9	?	Failure (44 h)
11	BG91-V	Brake	4.6	5.3	3.8	
12	BG91-V	No-Load	56.4	0.2	0.0	
13	SG59	Drive	35.8	6.9	1.6	
14	SG59	Brake	35.8	6.1	0.6	
15	SG59	No-Load	56.4	0.4	0.4	
16	Stock	Drive	2.7	6.5	10.6	Failure (23 h)
17	Stock	Brake	2.7	5.8	4.3	
18	Stock	No-Load	7.5	0.3	10.8	Failure (39 h)

Table 4. Average No-load Current

Brush	Test #1	Test #2	Test #3	Test #4	Test #5
Material	Ambient	CO2	CO2	CO2	Vacuum
SG54-27	0.45	0.42	0.51	0.54	0.51
SG54-27-V	0.90	0.80	0.84	0.99	0.51
BG91	0.34	0.40	0.18	0.09	0.09
BG91-V	0.45	0.35	0.21	0.21	0.30
SG59	0.74	0.83	0.42	0.51	0.57
Stock	0.51	0.50	0.51	0.60	0.42

Table 5. Input power, Output Power, and Efficiency

Brush Material	Test #3 (CO2)			Test #4 (CO2)			Test #5 (Vacuum)		
	Input W	Output W	Out/In %	Input W	Output W	Out/In %	Input W	Output W	Out/In %
SG54-27	9.4	3.2	34	9.2	3.1	34	9.7	2.4	25
SG54-27-V	10.7	3.2	29	10.7	3.1	29	9.0	2.6	28
BG91	9.8	3.0	31	9.4	2.9	31	8.3	2.2	26
BG91-V	9.4	3.0	32	9.4	3.0	32	8.3	2.2	27
SG59	9.4	3.5	37	10.2	3.5	34	9.2	2.8	30
Stock	10.6	3.5	33	10.5	3.4	33	9.0	2.7	30

Figure 2. Close-up of Brushes and Commutator – BG91 Drive Motor Shown at Completion of All Testing

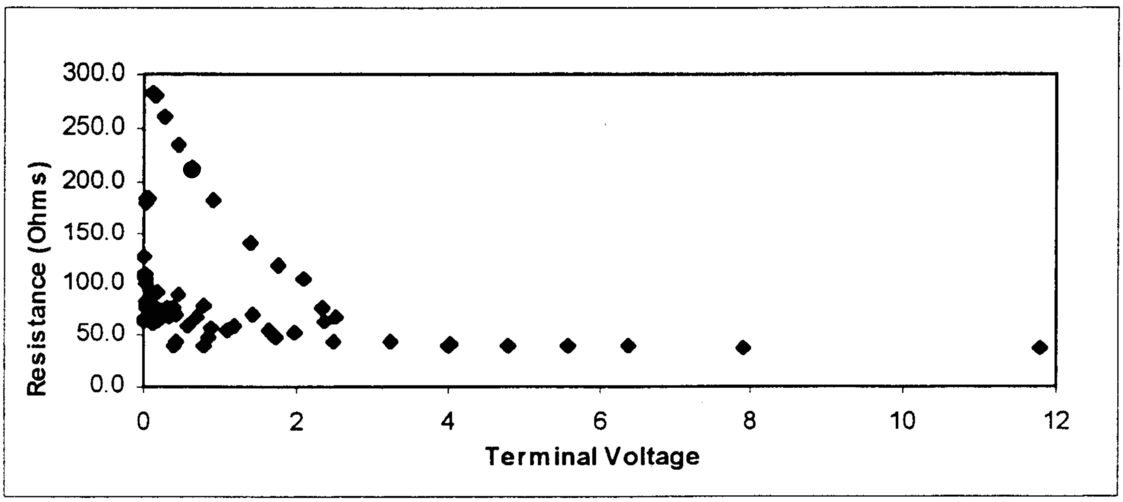

Figure 3. Resistance vs. Voltage for Motor with BG91 Brushes

CONCLUSIONS

Brush Materials

There are several important characteristics of motor brush materials that need to be considered in determining suitability for a particular application:

- Wear rate
- Cohesiveness of the debris; tendency to pack into commutator slots
- Electrical properties of the debris; tendency to short between commutator segments
- Contact resistance between brush and commutator

In a low-pressure CO_2 environment, SG54-27 appears to be the best overall choice for long life with good performance. Stock copper-graphite brushes worked well, but with higher wear rates; this would be a practical alternative for motors in applications that do not require long life, such as deployment devices. BG91 displayed low wear rates, high contact resistance, and low no-load current; this material might be the best choice for an application where no-load power must be minimized. SG59, with its low contact resistance, might be a good choice where power throughput must be maximized. The addition of wet lubricant to the brushes appears to be detrimental in CO_2; wear rates are not reduced measurably and the brush debris becomes more cohesive.

In vacuum, the SG54-27-V, BG91, and SG59 materials performed about as well as they did in CO_2. All other materials had excessive wear and/or failures. Usage of SG59 is questionable for anything other than very short durations, due to the higher wear, commutator abrasion, and unsatisfactory results in a previous vacuum test[2]. If SG54-27-V is used, one must be extremely attentive to debris build-up in the commutator slots, especially if there are periods of non-vacuum operation. BG91 appears to work well under all conditions, although there is very little flight history for this material. The high contact resistance of BG91 gives lower electrical efficiency and variable ohmmeter readings, making it difficult to assess motor health prior to operation. It is not clear if this characteristic (plotted in Figure 3) could produce other problems.

The failures in vacuum all appear to follow the same sequence: brush debris in the commutator slots forms a partial short, leading to increased power draw and heating. The increased heat load causes the rotor temperature to rise until the winding insulation fails. This is especially serious problem in vacuum, where heat dissipation from the rotor is poor.

General Recommendations

These test results, while encouraging, do not show that brush motors have the high reliability of a well-designed brushless motor. The problems associated with sliding contacts – wear, conductive debris, non-conductive contamination – are continuing major sources of concern. In addition, the rotors are subject to higher temperatures, thermal cycling, and mechanical stress, which could lead to insulation failure or wire breakage. However, where resources (mass, power, funding, schedule) are limited, brush motors may be the only viable choice to provide the desired actuation. To reduce the inherent risks, it is important to select the appropriate materials for the application and perform representative tests in the expected environment. Motor current and/or temperature should be monitored to avoid catastrophic failure due to overheating.

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